



# Lithium ion battery production

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## ABSTRACT

Recently, new materials and chemistry for lithium ion batteries have been developed. There is a great emphasis on electrification in the transport sector replacing part of motor powered engines with battery powered applications. There are plans both to increase energy efficiency and to reduce the overall need for consumption of non-renewable liquid fuels. Even more significant applications are dependent on energy storage. Materials needed for battery applications require specially made high quality products.

Diminishing amounts of easily minable metal ores increase the consumption of separation and purification energy and chemicals. The metals are likely to be increasingly difficult to process. Iron, manganese, lead, zinc, lithium, aluminium, and nickel are still relatively abundant but many metals like cobalt and rare earths are becoming limited resources more rapidly.

The global capacity of industrial-scale production of larger lithium ion battery cells may become a limiting factor in the near future if plans for even partial electrification of vehicles or energy storage visions are realized. The energy capacity needed is huge and one has to be reminded that in terms of cars for example production of 100 MWh equals the need of 3000 full-electric cars. Consequently annual production capacity of  $10^6$  cars requires 100 factories each with a 300 MWh capacity. Present day lithium ion batteries have limitations but significant improvements have been achieved recently [1–8]. The main challenges of lithium ion batteries are related to material deterioration, operating temperatures, energy and power output, and lifetime. Increased lifetime combined with a higher recycling rate of battery materials is essential for a sustainable battery industry.

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## 1. Introduction

Metals and metal products play important role in our industrial development. Sustainable use of the earth's resources in metal products production, end use, and recycling of metals has to be taken into account. Lithium ion batteries have developed rapidly and different types of chemistry have successfully been introduced. Common applications are power sources for cell phones, laptops, and other portable devices. Development is currently going on in larger applications such as energy storage, partly or fully powered electric vehicles, industrial vehicles, lifts, cranes, harbour machines, mining vehicles, boats, and submarines. Production of cells and battery management system electronics scaling from the individual cell to large modular solutions are ramping up globally. These new applications demand huge amounts of specially made products (copper and aluminium metal foils, electrolyte, lithium metal oxide, separator polymers, binders, graphite, conductive additives, cover bags, tabs, and production hardware). Over the long term, diminishing amounts of easily minable metal ores sites influence material availability. Iron, manganese, lithium, and nickel

are still relatively abundant but metals like cobalt, and rare earths are becoming limited resources in coming decades.

The driving force behind this growing interest in Li-ion batteries is both the desire to increase energy efficiency and to reduce consumption of hydrocarbon-based fuels. The deployment of battery systems and the battery industry are expected to grow rapidly over the next 2 to 3 years.

The main challenges of Li-ion battery technology are related to chemistry, material deterioration, lifetime, operating temperatures, energy and power output, and, scaling up, long term material supply for some, and overall costs. Cost targets for Li-ion batteries are ambitious, only a couple of hundred dollars per kWh, while currently the price is closer to \$1000 per kWh. In the near future, the price is expected to decrease only modestly due to more challenging chemistry and safety requirements of the electric vehicle (EV) industry.

Batteries are specific in their uses and one type does not fit all purposes. Challenges appear, for example, when individual cells are combined into in larger battery systems. In larger combinations, cooling is required to avoid hot spots and deterioration of lifetime due to overheating. Thermal control is also necessary for safety reasons.

Advanced Li-ion battery systems include electronic control known as the battery management systems (BMS) which is crucial when operating electric vehicles (EV), and hybrid electric vehicles

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### Abbreviations

LFP      Lithium iron phosphate  
 NCA      Lithium nickel cobalt aluminium oxide  
 LCO      Lithium cobalt oxide

NCM      Lithium nickel cobalt manganese oxide  
 LMO      Lithium manganese oxide  
 SOC      State of charge

(HEV). BMS also prevents battery overcharging and deep discharging of the battery.

## 2. Lithium ion batteries

Batteries are devices that convert stored chemical energy into electricity within a closed system. Electrochemical conversion occurs at two electrodes, viz., cathode and anode. The nature of the reaction is dependent on the chemistry of the electrodes. The power of the battery is more determined directly by the area of the electrodes in contact with the electrode while the energy content depends more on mass and volume of the active material. In a rechargeable battery (secondary battery), if the external load is replaced with power supply the direction of electrons (and lithium ions) are reversed, and the battery is charged. Lithium ions ( $\text{Li}^+$ ) move from anode to cathode during discharge and from cathode to anode in charging. Electrons move in the external circuit into the same direction as  $\text{Li}^+$  ions. The anode (negative electrode) is usually graphite or lithium titanate. The cathode (positive electrode) is typically lithium metal oxide [1–6].

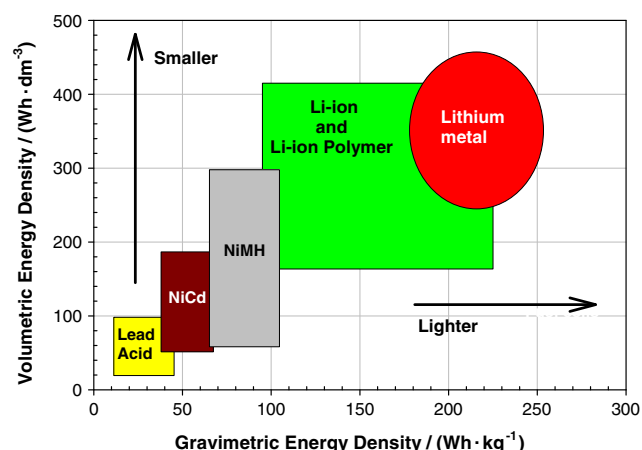
Lead acid, nickel-metal hydride, and lithium ion batteries are the most common rechargeable batteries. Lead acid battery technology is well proven and is more than a century old. However the lead acid battery shows low gravimetric and volumetric energy density.

Nickel-metal hydride batteries provide reliable cyclability and are commonly used in hybrid vehicles. Their downside is a relatively low energy density and low cycle life and relatively high self-discharge rate up to 10% per month. That makes lithium ion systems an attractive alternative. Figure 2 shows crudely volumetric and gravimetric energy densities for some common batteries.

Lithium ion cells provide a cell configuration that operates at over twice the potential of lead acid or NiMH cells. The reactivity of lithium has been problematic and the low cycle life has been a problem especially under high current densities. However, modern lithium based electrodes provide much better power density and cycle life, and as a result lithium ion cells are being considered for use in larger applications like vehicles.



**FIGURE 1.** Rechargeable lithium ion battery cell (above) and cell frame, module, and larger system (below). The module and system include BMS and temperature control.



**FIGURE 2.** Plot of volumetric energy density against gravimetric energy density for common batteries [8].

Battery electrodes provide electron conductivity outside, they store chemical energy, and generate electrical energy by releasing of stored energy.

All these functions should be completed isothermally, and with as little mechanical or chemical strain as possible. New novel lithium cathode materials are continuously developed in universities and company research laboratories to improve battery performance, lifetime, thermal tolerance, power performance, energy density and charge rate, as well as to obtain desired size, thickness, and flexibility.

## 3. Chemistry

Lithium cobalt oxide,  $\text{LiCoO}_2$ , is the oldest type of lithium-ion batteries. It has been produced since 1991 (Sony). Many other structures developed since which include  $\text{LiCo}_{1/3}\text{Ni}_{1/3}\text{Mn}_{1/3}\text{O}_2$  (NCM),  $\text{LiMn}_2\text{O}_4$  (LMO),  $\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$  (NCA), and  $\text{LiFePO}_4$  (LFP). Figure 3 shows an overview of lithium iron phosphate



**FIGURE 3.** Overview of one of LFP electrode coating lines in European Batteries plant at Varkaus, Finland. The annual capacity of the plant is 100 MWh [9].

(LFP) electrode coating line. LFP is coated on special made thin aluminum foil keeping coating thickness and weight per surface area uniform. Separate lines for both cathode and anode are needed. The coated electrode is tried in the long oven shown in the figure. The electrode is rolled at the end of the coating line and goes through many process steps including calentering, slitting, notching, and drying. After that the electrode is ready for battery assembly in the dry room where cathode, anode, separator, cover bag, and electrolyte are put together.

Lithium cobalt oxide cells benefit from well established powder and cell production processes. Hundreds of million cells are produced annually. Cobalt based cathodes are easier to produce than LFP-based cells. Currently there exist tens of manufacturers for different battery applications, variations, sizes and shapes. The move from small cell sizes to large-format cells has caused new safety issues to cell manufacturers. Novel new materials like LFP have been introduced to increase the safety in large-format cells. Table 1 shows some common lithium ion battery chemistries, their uses, characteristics, relative cycle lives, and nominal voltages.

The most recent lithium-ion cathode material: discovered 1995 and development to commercial products started in 1997. The  $\text{LiFePO}_4$  (LFP) is considered the most promising lithium-ion technology for large-format batteries due its long cycle life and safety. The LFP material is still in the pilot phase and powder production is ramping up from pilot-scale to mass production. The production of high quality LFP-powder is difficult.

The advantages of  $\text{LiFePO}_4$  (LFP) are summarized as follows. LFP shows reasonable good cell voltage 3.2 V depending on the active materials and it also shows extremely good safety features.  $\text{LiFePO}_4$  powder is non-toxic, shows no thermal runaway, and is chemically stable. It shows long cycle (+4000 cycles) and calendar life (+5 years), and reasonably large energy density, (110 to 150)  $\text{Wh} \cdot \text{kg}^{-1}$ , 1/4 weight and 1/3 size of lead acid batteries. The charging time is short, viz., 1 h and even half an hour. The self-discharge rate of a LFP battery is extremely small and it can be stored fully charged or partially charged, unlike a lead acid battery. Figure 4 shows the typical flat discharge curve for  $\text{LiFePO}_4$  chemistry. From the figure, one can see that the voltage remains almost stable and independent of

discharge over a wide capacity% (SOC) range. Overcharging the cell does not cause major problems below 4.5 V.

Also hard short-nail penetration may cause minor smoking but no propagation, see figure 7. In the case of overheating, LFP does not react prior to pressure/electrolyte release in a pouch cell which minimizes the thermal runaway that is more likely with energetic oxide materials like  $\text{LiCoO}_2$ .

Figure 4 shows discharge curves of 42 Ah capacity battery based on LFP chemistry. The lithium iron-phosphate (LFP) cell has a very stable discharge voltage. The only drawback of stable voltage behaviour, as in figure 4, is estimation of the state of charge (SOC). Due to a nearly constant voltage from 5% to 80% state of charge, estimation of SOC is usually based on coulomb counting (integration of current).

The temperature range of operation for special purpose batteries or vehicle applications is from  $-40^\circ\text{C}$  to above  $100^\circ\text{C}$ . In practice, current lithium-ion batteries operate within the temperature range  $-20^\circ\text{C}$  to  $60^\circ\text{C}$ . Development is underway to improve the low temperature and high temperature performance, and lifetime at higher temperatures.

Low temperature performance is limited by temperature dependencies of electrochemical reactions, transport properties and phase changes of the electrolyte. Good ionic transport properties correspond to high conductivity, low viscosity, and sufficiently high diffusion coefficient of  $\text{Li}^+$  while charging and discharging the battery.

At lower temperatures the capacity (in Ah) of the cell falls and the voltage drops. This behaviour is shown in figures 5 and 6. The C-rate corresponds to the current at which useful capacity of the battery is consumed with time  $t$  in hours. It is also the charge or discharge rate. A 1C discharge or charge occurs a 1 h; 0.5C discharge or charge occurs in 2 h, etc.

#### 4. Abuse tolerance

Lithium iron phosphate has increased safety compared to other lithium chemistries. Also Lithium titanate is considered as safe as LFP. Figure 7 shows EB's cell after putting six zinc plated iron nails through the cell. No smoke or fire was observed and the cell voltage

TABLE 1

Properties of different lithium ion cathode materials. Cycle life depends how the testing has been carried out [1,7,8].

Cathode	Formula	Type	Energy density/( $\text{Wh} \cdot \text{kg}^{-1}$ )	Energy density/( $\text{Wh} \cdot \text{dm}^{-3}$ )	Relative cycle life	Voltage/V
LCO	$\text{LiCoO}_2$	Energy/power	170 to 185	450 to 500	1	3.65
NCM	$\text{LiCo}_{1/3}\text{Ni}_{1/3}\text{Mn}_{1/3}\text{O}_2$	Energy	155 to 185	330 to 365	3	3.7
NCA	$\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$	Energy/power	145 to 165	270 to 350	3	3.65
LFP	$\text{LiFePO}_4$	Energy	100 to 140	200 to 330	>4	3.2
LMO	$\text{LiMn}_2\text{O}_4$	Energy/power	90 to 120	260 to 300	1	3.8

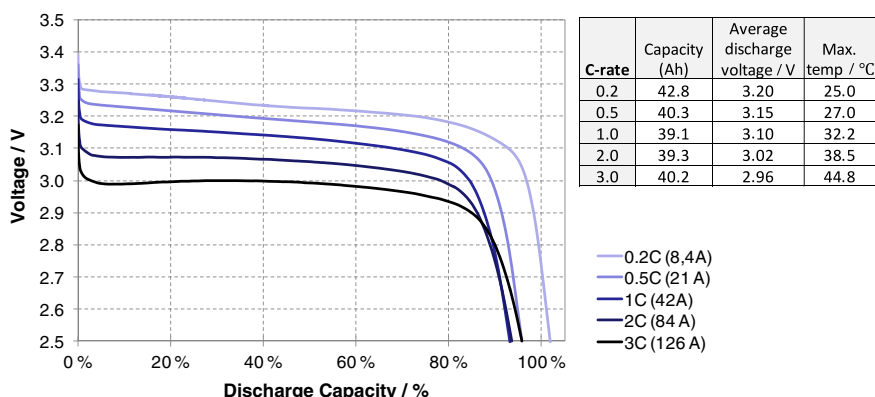
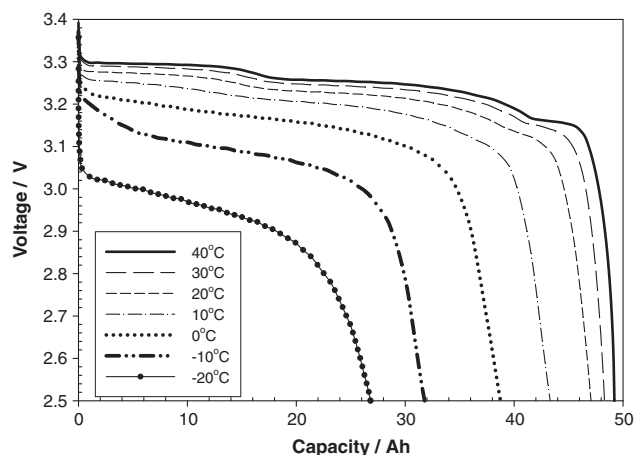
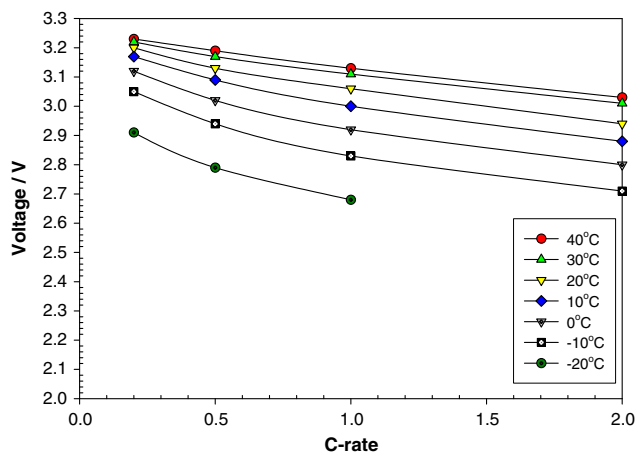


FIGURE 4. Plot of voltage against discharge capacity for the 42 Ah capacity LFP battery cell. Measurements were carried out at room temperature.



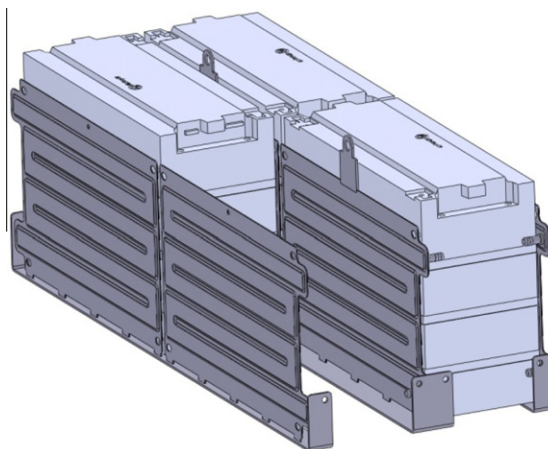
**FIGURE 5.** Plot of voltage against capacity to show typical capacity curves for lithium iron phosphate cell at different temperatures. All curves were measured at 0.2 Charge-rate (C-rate) i.e. discharging rate takes 5 h from fully charged to 2.5 V cut off voltage.



**FIGURE 6.** Plot of discharge voltages against the charge-rate at different temperatures.

remained above 3 V overnight. That was an example of a safe soft cell shortage. In another experiment, a charged cell was immersed into artificial seawater. The electrolysis reaction of water powered by the battery cell occurred, evolving oxygen and hydrogen gases. Water electrolysis reactions ceased after two of hours and the cell remained stable underwater for six week testing period.

The standard abuse tolerance tests by the United Nations include, for example, a 9.1 kg weight dropped on the side of the battery,



**FIGURE 8.** Example of arrangement of cooling elements in a battery pack.

thermal tests, altitude test, vibration, external shorting, overcharging, and forced discharge. The United Nations tests refer to recommendations on transport of dangerous goods which lithium ion batteries have to pass in order to be eligible for transportation.

## 5. From a cell into a system

There is often confusion in the terms used to describe the various components of a battery system because the word “battery” is used when referring to both a single cell and for example a 12 V car battery comprising six cells. In this paper, we use the following terms (see figure 1):

- **Cell:** The most basic element of a battery (nominal voltage 3.2 V for a LFP cell).
- **Module:** A collection of cells connected in series/parallel providing a higher voltage and capacity than a single cell. A module includes a measurement unit (slave unit) of the BMS.
- **Pack:** A collection of modules connected in series and located in a single enclosure.
- **System:** One or multiple packs connected in series/parallel including the cooling system, the BMS master unit and the peripherals.

The modules are built up with a stackable frame that allows modules of variable length to be built using the same mechanical components, and a rigid and lightweight structure (energy density is always somewhat lower in a system or in a module compared to individual cell).



**FIGURE 7.** Example of abuse tests of charged cells. Nail and hammer treatment (left) and seawater immersion (right).



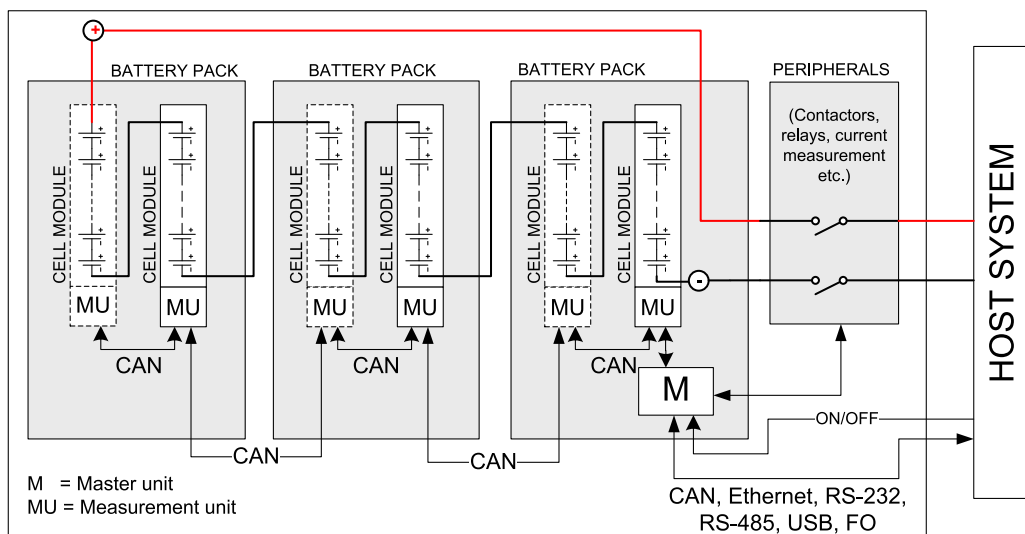


FIGURE 9. Block diagram of the EBattery™ battery management system [8,9].

Thermal management is one of the biggest challenges in the development of a battery pack. Although the efficiency of a lithium ion battery is significantly higher than of conventional batteries (e.g. lead acid), the dissipation may limit the performance of the battery system under hot conditions. Operating the battery in a high temperature environment may result in premature ageing, irreversible effects and even safety problems. Similarly, the battery pack must be heated in cold conditions. Due to IP requirements of the pack, ambient air cannot usually be used as a coolant. Therefore, a liquid circulation through the pack or a heat exchanger is required. Figure 8 shows water cooling elements that are designed for EBattery30 modules.

### 5.1. Battery management system (BMS)

A lithium-ion battery stack comprising several cells cannot be operated as if it were a single power source. Lithium-ion cells are very susceptible to damage outside the allowed voltage range that is typically within (2.5 to 3.65) V for most LFP cells. Exceeding this voltage range results in premature ageing of the cells and, furthermore, results in safety risks due to the reactive components in the cells. This is why a proper battery management system monitoring individual cell voltages and temperatures is necessary.

The variation of the electrical characteristics (capacity, internal resistance) caused by manufacturing differences, ageing and unequal temperature distribution can result in deviations in the state of charge (SOC) inside a battery stack. If the SOC is not periodically *balanced* some cells may be eventually overcharged or over discharged, leading to irreversible damage, and eventually complete battery stack failure. This process is inherently divergent, and reduces the available capacity even if the damage can be avoided by careful voltage control [11].

A conventional *passive* balancing method is to connect a load resistor parallel to each cell to discharge individually selected cells. This method is only suitable in the charge mode to suppress a voltage rise in the strongest cells, and can be used for a periodical equalizing of the battery stack. *Active* balancing means a method that transfers energy between battery cells instead of dissipating. A bi-directional balancing module can both charge and discharge an individual cell. The balancing can be based on real-time cell voltages or estimated capacity distribution of the stack defined by an adaptive algorithm during previous load cycles.

The core functions of a BMS systems are as follows [10]:

- Prevent the voltage of any cell from dropping below a limit by reducing discharging current, asking it to be reduced.
- Prevent the voltage of any cell from exceeding a limit by reducing charging current, stopping the charging or asking it to be stopped.
- Prevent the temperature of the battery system from exceeding a limit by reducing battery current or asking for cooling.
- Prevent charging/discharging current from exceeding a limit that depends of battery temperature, SOC and various other parameters.
- Provide relevant status information (e.g. SOC, SOH) about the battery pack to the host system and the user via a data link.

### 5.2. Topology and communication of the BMS

The BMSs are often categorized based on how they are installed; directly on each cell or centralized in a single device, or in some intermediate form. The various topologies are as follows [8]:

- *Centralized*: BMS is located in a single assembly that is connected to cells with a cable harness.
- *Modular*: BMS comprises multiple identical cards one of which is designated as a master, and the cards communicate with a data link (e.g. CAN bus).
- *Master-slave*: The system comprises multiple identical cards (the slaves), each measuring the voltage of a group of cells, and a separate master unit that handles computation and communications.
- *Distributed*: The voltage (and temperature) of each cell is measured by a card connected directly to the cell. The cells are connected via data link to a controller that handles computation and communications.

A simple BMS often uses digital signals to report to an external device or system the state of the battery pack. These on/off signals indicate the status of a fault/alarm and if a certain operation is enabled (charging, discharging).

In a more advanced application, the BMS master unit uses a data link to communicate with the host system. The data link can be proprietary or use a standard protocol, but even in the latter case, the coding of the data is usually proprietary. The most common standards are RS232, RS485, CAN bus, Ethernet and USB. Figure 9 shows block diagram of EBattery™ management system [8,9].

The CAN bus is the standard in vehicles and most industrial applications. Industry groups have attempted to define the application layer with a set of standard messages, such as SAE J1939 and CANopen. None of them is focused on the functions of BMS, and therefore each OEM and BMS designer defines CAN messages differently [8]. However, standard device profiles for CANopen have been defined for a battery and a charger (CiA 418/9).

## 6. Conclusions

Lithium ion battery technology has developed hugely in recent years. This is due to new lithium electrode materials which have improved the battery performance towards needed targets. The lifetime can be extended by using clever algorithms in a battery system and keeping the system temperature sufficiently low. The battery management system (BMS) is crucial for larger battery systems. Lithium-ion cells are very susceptible to damage outside the allowed voltage range that is typically within (2.5 to 3.65) V for most LFP cells. Exceeding this voltage range results in premature ageing of the cells and, furthermore, results in safety risks due to the reactive components in the cells. This is why a proper battery management system monitoring individual cell voltages and temperatures is necessary. The chemistry, cell and system construction are under intensive development resulting in improvements of temperature tolerances and lifetime. The future development is towards increasing efficiency in materials and energy usage in production. Also the trend is to use less toxic materials and solvents in

production. The recycling of materials is taken seriously and is also increasingly mandated by legislation.

## Acknowledgements

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